Increasing axle load in Europe
State of the art and perspectives

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Summary: The freight transport in Europe is growing rapidly and the European Commission published its strategy for the revitalisation of European rail transport in its white paper of 2001 ‘European transport policy for 2020: Time to decide’. Currently investigations are being carried out for improvements in international freight transport. The increase in axle loads is one of the possible improvements.

The current standardised UIC maximum axle load of 22.5 tonne results from the rail infrastructure, rolling stock and related rail technology and maintenance developments.

On the other hand, it is clear that heavier axle loads shorten track component lives, increase the rate of degradation of the track structure and may increase the risk of derailments. Likewise, the wagon-maintenance costs may increase with increased wagon loading. There still is no common standpoint on what the ‘optimum’ heavy axle load would be. The various operators favour 25 or even 30 tonne.

The paper focuses on the state of the art in Europe giving an analysis of influencing parameters relevant to the European situation.

It will be presenting some case study as examples for using increased axle load in Europe comparing them to those from non European examples.

Based on the investigation a recommendation will focus on the European possible perspectives.

1 Introduction

The freight transport in Europe is growing rapidly and the European Commission published its strategy for the revitalisation of European rail transport in its white paper of 2001 ‘European transport policy for 2020: Time to decide’.

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Based on the investigation a recommendation will focus on the possible European perspectives.

2 Influencing parameters of heavy axle load

There are enormous complexities associated with quantifying answers in the area of increasing axle load. Each element of the track structure responds differently to changes in axle loads, depending on its design and composition as well as on its interaction with other components. In addition to this,
there are the complexities associated with dynamic loads developed from track or wheel irregularities of varying magnitude.

However, in this chapter, an analysis will be given of all influencing parameters, based on the world wide experiences. The goal of this chapter is to give a wide analysis so that every UIC member can take out the elements that are the most applicable to its specific situation.

2.1 Infrastructure

A vast expertise (simulation, assessment of residual service life, implementing reinforcement method) has been established by the railway organisations that operate high axle load freight. Some of it is directly transferable to the UIC context.

2.1.1 Bedding

In the end, the entire load rests on the bed structures, i.e. the bedding ground and the bridges. Even though the dynamic effects exerted here are not as intense and complex as they are at the wheel-rail interface, the loads increase at least in proportion to the axle load. Therefore they pose problems to the bearing capacity of these structures, their fatigue and their behaviour under load.

Points of attention are:

- The dispersion of the loads. Depending on the quality of the soil and the climate (e.g. a very damp climate with periods of frost), large-scale reinforcements might be necessary (increased substructure, incorporated asphalt, geotextile, drainage, etc.).

- In addition to the bearing capacity, ground subsidence must be scrutinised carefully and particularly its dispersal; significant dispersal can, in fact, lead to greater dynamic effects at rail level.

- The stability of high embankments.

- The specific mixed traffic problems (speeds and cant deficiency, train lengths etc.).

Although there is not really any superior technical control to be acquired, the problems posed to the engineer can become considerable and may lead to very severe conditions, or even total reconstruction.

2.1.2 Bridges

The operation at increased axle load may lead to difficult problems in the near future, as the existing bridges were not designed originally to sustain such loads. Referring to the experience in the US, very rapid deterioration is likely to occur in the short term with adverse consequences on the safety level and on the expenses for maintenance and renewal. Bridges are always recognised as critical elements of the line; it is commonly acknowledged that even if the piers do not cause problems, the support elements usually do. The hierarchy between critical elements of the structure depends entirely on the design of the main members and assembly joints, the steel bridges (in particular the old ones) concentrate most of the uncertainties. Especially in these steel bridges, the joints are critical.

A number of techniques have been developed to reinforce existing bridges: e.g. pre-stressing, bonding of external reinforcement. All of these methods combine numerical simulations for the assessment of the residual service life and reinforcement techniques. In general, composite materials seem to be the way of the future, even if they are still expensive.

The calculation methods for bridges are relatively precise and, moreover, a high proportion of existing bridges are very old. As the calculation rules have constantly evolved towards heavier loads, there is a high risk of reducing the remaining useful life and even of exceeding the bearing capacity. This applies to the deck in general, but, more particularly, to the short components, such as metal deck girders as well. The distribution of the axle loads (and their dispersal) is essential for determining the calculation load of the bridges. The margins for the dynamic coefficients due to the dynamic effects of steam locomotives for old bridges (coefficient can reach 2) and – fairly arbitrarily and somewhat underestimated – track defects (coefficient j).

The real situation regarding the stability of bridges is often better than expected; this depends on the characteristics of the building materials. The most advanced lines and freight networks have only encountered any real problems above 30 tonne, but for the multi-traffic European networks the limit would have to be below 30 tonne, probably around 25 tonne.
Essential prerequisites for any additional increases in axle load and speed:
- Utilisation of modern running-gear designs
- Ride tests using measuring wheelsets on track of different qualities
- Utilisation of matching pairs of wheel/rail profiles
- Long welded rails
- Good quality of track
- Limiting of speed in tight curve radii

2.2 Wheel-rail interface

This is without doubt the most difficult and complex element of high axle load operation. It encompasses the forces of interaction between axles and bogies on the one hand and the track on the other hand. The dynamic impact effects are particularly numerous and complex and they can involve very large increases in the quasi-static stresses.

These increases may lead to problems of safety (derailment, lateral stability of the track, shunting). It is therefore necessary to make fundamental modifications to the design and maintenance of the equipment and components affected, particularly the wheels and rails. The following factors are necessary in order to maintain control of the system:
- using materials of superior quality,
- achieving a high degree of cleanliness of any inclusions,
- increasing the dimensions if necessary,
- developing new technologies (steering axles, improved suspensions),
- a grinding and a lubrication strategy for the maintenance

The primary objective is to simultaneously minimise wear and avoid defects. These defects may lead to fractures and may be the source of impacts. In general, improvements must be made to the maintenance techniques, the objective being always to control wear and defects, including geometric defects. All of this involves fundamental changes, which must, in principle, be the subject of studies and tests. However, reference can be made to documents produced by the IHHA.

2.3 Rolling stock

This includes two issues: increasing wagon size (introduction of new equipment) and increasing the load of existing wagons (new braking and suspension solutions, wheel/rail forces exerted by vehicles especially in different curves). In terms of rolling-stock engineering, increasing axle loads is primarily a problem of running gear. The current market for running gear for high axle loads is not as big for two-axle wagons as for two-bogie ones.

Special care must be given to the selection of the wagon type that will be used as the impact of heavier wagons is of primary concern. In fact there are well known cases of difficulties.

Transferring technologies from abroad: the risks

In England where the bogies initially used for 25 tonne axle load, were 3 piece bogies as used in the USA. These bogies had a high unsprung weight and were soon identified as creating increased track damage and plans were quickly drawn up to replace them.

Furthermore, the bogies had high maintenance costs due to the different track parameters, (many tight curves in the UK versus mainly straight track, in the USA). Ultimately the bogies were replaced by the so-called primary suspension bogies, which rode and curved better but at higher costs.

By reducing the impact and dynamic loads into the track structure, the life of track components should be increased. Points of attention that may lead directly to a significant increase in the life span of the rail and the fastener:
- Wheel/rail forces exerted by the vehicle (vertical, lateral and longitudinal)
- Size of allowable wheel flats
- Limits of out of round wheels
- Limits of allowable surface defects, such as shells
Instability problems
- Mechanical design of car bodies and mechanical elements.

The areas in this mechanical design that need to be investigated, include:
- The effect of reducing unsprung mass. Design work in the suspension area may reduce this effect.
- Improved curving performance while reducing vertical forces (e.g. self-steered wheelsets).

2.4 Decision making process

The benefits or drawbacks of an increase in axle loads are very line specific (nature of the route, traffic density in relation to capacity, nature of the commodity, condition of the bridges, et cetera). Therefore a line specific cost benefit analysis is unavoidable in the decision-making process concerning an increase in axle loads.

2.4.1 Economical analysis

In general, the introduction of wagons with high axle load (25-35 tonne) is profitable when bulk traffic has to be transported on specific routes. A significant increase in the axle load involves a complete alteration of the way in which the technical problems are controlled. It also leads to fundamental changes in the balance between income and expenses.

The cases that have been analysed in WP1 showed that heavy axle load operation makes economic sense, of course dependent on the overall track quality and the speed with which the trains can operate over those tracks.

It is necessary to draw up a comparative balance sheet between additional income and expenditure. Normally, the operating costs are by far the most important, so the overall balance will often be positive, however, it may depend largely on the individual case:
- curves
- gradients
- freight alone or mixed

- frequency of heavy traffic
- electrification

2.4.2 Main steps in the decision-making process

The most important thing to bear in mind is the overall approach to the upgrading. New wagons with heavier axle loads must be accompanied by different maintenance practices to reduce the impact on the rail and, if economically justified, by the adoption of new bogies that can significantly reduce rail wear.

The most important problems are related to the sections of the line where the formation structure is poor. In that case the heavier axle load will accelerate the degradation of the line and maintenance work cannot be sufficient. So it is necessary in the preliminary phase to identify the weak sections and to reinforce them in advance.

The results of this and other studies highlight the importance of the right configuration of vehicle-track matching, which is to be co-ordinated and harmonised on an international level.

The main steps in the decision-making process (for a specific line)

- Identifying the need for a higher capacity.
- Identifying the effect of increased axle loads on the components of track structures.
- Executing case studies to identify the best-suited vehicle-track configuration.
- Executing a life cycle cost study of the system.
In general, it will be useful to take precise, quantitative evaluations as a basis, such as can be obtained using software. Such software already exists and is usually supplemented by economic calculation sheets. Organisations, other than the rail networks may also be interested (shippers, wagon owners, industry, etc.).

2.4.3 Methods/Tools

The increase in axle load may lead to complex technical problems, because of the risk of exceeding the limits of the structures that support the railway. It would be tedious to quantify the additional expenditure element by element, but global, parametric formulae have been put forward for the track expenditure. Even though it is risky to extrapolate the results, since these formulae are often established for existing axle loads and do not include bridges, they allow a quick comparison of the parameters. It is also possible to draw on the work carried out by more advanced networks and on documents produced by the IHHA.

To estimate the increase in track maintenance costs, the ERRI D 161 project has developed a method to be used for the calculations. This method is based on defining the rate of track deterioration caused by an increase in axle load from 20 tonne to 22.5 tonne. This is the value corresponding to a certain tonnage over the initial zero tonnage, e.g. for geometry of the track after a maintenance operation.

Another method is the one used by Banverket. Its ’Model to predict track degradation costs’ separates the track degradation into fatigue and wear of the track. It does this in using a systematic approach by identifying the cost elements of track (as a function of curvature) and of vehicle elements (as a function of vehicle technical capability) taking into account the annual tonnage on the line. This method gives a more precise evaluation for economical calculation.

Several models related to heavy haul (cf. Bibliography, A.M. Zaremski):

- Train calculation models for calculation of running times, maximum train weight, fuel consumption etc.
- Engineering damage models for the calculations of additional damage to track components, switches, sleepers, ballast and subgrade.
- Simulation models for calculating the increased dynamic behaviour of wheel, axles, wagon bodies, braking systems and coupling systems.
- Simulation models for calculating the increased dynamic behaviour of bridges and structures.
- Financial model for calculation of annual and life cycle costs.

The question whether to increase axle loads is rather an economical question than a technical one. Nevertheless, the key point in this question remains a technical one, since it is to determine the extra maintenance cost and therefore to measure the increase in track deterioration.

2.5 Recommendations

Full customer service continues to be a driving force for freight business, which operates in competitive markets. Applying increased axle loads therefore is a customer-oriented development.

2.5.1 Recommendations

Partners: The results of investigations show that a strong relationship between the partners of the system is key (customers, railway civil, vehicle engineers, rail and vehicle provider industry and authorities).

Integration: A systematic and line specific approach is unavoidable. New maintenance policies and new control systems are necessary to manage the increased requirements of the track structure, due to increased dynamic forces in operating higher axle loads. For the bridges a step-by-step investigation is necessary.

Vehicle/track system: The technical performance of the vehicle should be taken into account since it can actively contribute to the decrease in track deterioration. For the right configuration in terms of the vehicle/track system, a twofold approach is recommended, that is to compare the simulation tools with the test results.

Economic analysis: The technical analysis is only the basis for the decision-making process; the economical results are determinative. All the above mentioned activities need to be verified by using cost-benefit economic calculations and life cycle cost calculations before decisions should be taken on applying increased axle load operations on a given line.
3 State of the art in Europe

Nordic Heavy Haul Group

The Nordic Heavy Haul (NHH) group was established in 1999 and became a member of the IHHA that same year.

The ‘Malmbanan’ railway line in the north of Sweden and Norway is a 540-km long single-track line, north of the Arctic Circle with harsh weather conditions in the winter. It links the iron ore mines and production plants (at Kiruna, Malmberget and Swappavaara) with ports and a steel factory (in Narvik on the Atlantic coast in Norway and Luleå on the Gulf of Bothnia in Sweden). The first stretch of the line was opened in 1888 carrying 1000 tonne of ore per train with wagons of axle loads of 11 tonne. In 1915, the northern section of the line was the first railway in Sweden to be electrified (15 kV, 15Hz). At present, the train consists of three-unit electric locomotives hauling 52 wagons (carrying 80 tonne of ore with an axle load of 25 tonne) having a total length of 470m. The annual transportation volume is about 20 million tonne of ore (25 million gross tonne MGT).

The LKAB mining company was created in 1996, to take over rail transportation operations on the ore line from the Swedish and Norwegian State Railways. The increased world competition (Brazil, Australia, Canada) and higher mining costs (depth about 1000 m below ground) have now forced LKAB to increased efficiency.

A complete investigation into the consequences of increasing axle loads from 25 to 30 tonne was carried out in 1996-97 by the two national rail infrastructure administrations Banverket and Jernbaneverket together with LKAB. Maintenance cost was studied by Luleå Technical University and the American consulting company Zeta-Tech using different approaches. Both studies indicated that 30 tonne axle load and longer trains would not significantly increase the maintenance costs for the track provided that the new rolling stock had an improved running performance of the bogies as compared to the present situation and that maintenance practices were enhanced.

A model to predict track degradation costs has been developed by Banverket to support the decision-making. Based on economic study and simulation results, it has been concluded that the upgrading to 30 tonne axle load will increase track structure maintenance costs by 3%. In the short term, an increase of maintenance occurs due to track settlement. However, a more cost-effective future use of infrastructure is expected by introducing preventive grinding and lubrication and by using rails with larger and hardened railheads.

LKAB has invested in new and improved track systems at terminals. This includes new track and electrification at Malmberget and a completely new terminal in Luleå. LKAB, Banverket and Luleå City have shared the investment costs of the new terminal and harbour in Luleå. The terminal is a closed system and has a very efficient internal logistics system.

A socio-economic analysis of the consequences of a possible upgrading has been made by Banverket and Jernbaneverket of the iron ore line to compare the upgraded and present situation. The most socio-economically profitable solution was chosen out of three possible alternatives. Based on previous experiences and the technical-economical study for using 30 tonne axle loads, a shift in focus from size to flexibility was done:

- better capacity utilisation
- IT based solutions for just-in-time logistics
- automation
- train control
- maintenance
- energy optimisation

A few examples of developments that are already taking place:

- Condition based maintenance of rolling stock, track and terminal equipment: GSM-R, the Global System for Mobile telecom for Railways, via condition monitoring onboard the locomotives, in terminals or via wayside sensors.
- New protocol standard ETCS, in combination with GSM-R will enable computer aided train dispatching.
- Communication, management and information system: IT based management.

Deutsche Bahn

DB has started regular operations of axle load of 25 tons on the line of Hamburg-Salzgitter at october 1st in 2003. Four daily iron ore trains with an overall weight up to 6000 tons are first step for DB into this new business. The traffic volume is around 5,5 million tons per year.

 Actually the permission of the railway authority is limited to three years. If the trains and the infrastructure will be operated without problems or significant wear released by the higher axle loads a permanent permission can be expected. Meanwhile further lines are in preparation to be opened for 25 tons axle load.

France National Railways (SNCF)

The SNCF has concluded a feasibility study on the state of the art of increasing axle loads, including the heavy haul experiences in Mauritania. This study stated that trains composed of wagons with axle loads >22.5 tonne and 8.0 tonne per meter can operate on designated SNCF lines.
The SNCF will launch on September 2005 the operation of heavy trains: 25 tons per axle, on an axis in the south of France, near Toulouse between “Cazeres sur Garonne” and “Portet St Simon”. The traffic volume is around 1 million tons per year.

The traffic consists of bulk stones

The reasons for this operation are:

- The same client at both ends of the trip
- The terminal lines are short, and can not be lengthened
- The strength of the existing wagons are capable of 25 tons per axle
- The existing traffic is limited by the number of train paths

The interests of the SNCF are:

- More traffic with the client
- Better use of the wagons
- Better use of the paths

The major interest of the client is the number of trains, which will decrease. There are some consequences:

- More traffic is possible with the same number of trains
- The traffic could be done from Monday to Friday instead from Monday to Saturday. There are two consequences
  - Use of the wagons for other traffic during the week end
  - Less time for the company workers (saving money)
- Less number of wagons for the same traffic

In France, in order to run new forms of operation, there is a strong safety procedure which has to demonstrate that the level of safety after the modification is the same as the level before the modification.

So, the SNCF has to write a Preliminary Safety Document to the Ministry of Transport, then a Safety Document which proves the safety level.

In order to operate this form of traffic, the following tasks have been done:

- Stability trials of the wagons running at 100 km/h on the line. The tests have been successful
- Braking trials. One wagon is “lose-shunted” by a locomotive at 100 km/h, so that the wagon is travelling alone and stops by emergency braking. The stopping distance is measured, and the behaviour of the braking system is tested. The results are not quite satisfactory. The wagons have to be modified in order to increase the braking performances in order to achieve the braking distance. On another hand, the braking shoes in cast iron are at the limit of their performance
- In order to be sure that the client does not load too many stones into the wagon, the SNCF will install a precision balance at the exit of the factory. This balance measures the weight of each axle when the train is moving before going on the main line
- The SNCF and the Infrastructure Manager will take care of the track. During 5 years, all the damages will be highlighted and compared with the existing damages in order to check the impact of increasing the axle load on the tracks
- The entire infrastructure is checked in order to allow 25 tons per axle. For example, sleepers with two concrete blocks which are on bridges will be replaced by mono- block concrete sleepers, in order to distribute the weight on the full length of the sleepers
- The organisation is organised in order that the wagons can not go out of the dedicated line. The wagons have special numbers, and will be recognisable by the operational staff.
- There is special training of the personnel who will be involved in that traffic

After this operation of heavy axle load trains, the SNCF will take the experience of the interest of such an operation, and could extend to other heavy traffics, such as for the steel industry.

**Finnish Rail:**

The Finnish Rail Administration has ordered a literature search made by Laboratories of Geotechnical Engineering at Tampere University of Technology and Highway Engineering at Helsinki University with the aim of taking 25 and 30 tonne axle loads into use.

The aim of the literature search was to summarise the effects that raising the permitted axle loads would have on ballast bed and substructure. Principal issues to be investigated in ballast were the effects of increased axle loads on the quality requirements of railway ballast and requirements for dimensions of the ballast bed. In substructure the investigation was focused on the material quality requirements, required dimensions of the structural layers and the available material models applicable in modelling of the mechanical behaviour of railway structures including the typical values of the parameters of these models. In addition, the quality requirements for frost insulation plates used in railway embankments and the possibilities to use asphalt materials in railway structures were also studied.
4 Perspectives in Europe

Rail freight traffic in Europe represents 30 % of the rail freight traffic in the world.

The evolution is contrasted:

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2002/01</th>
<th>2002/00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gtk in Europe</td>
<td>1991</td>
<td>2050</td>
<td>2140</td>
<td>- 4,4 %</td>
<td>+ 7,5 %</td>
</tr>
<tr>
<td>Gtk in EU (15 countries)</td>
<td>228</td>
<td>243</td>
<td>237</td>
<td>- 2,7 %</td>
<td>+ 3,9 %</td>
</tr>
</tbody>
</table>

Europe has an important network of canals and rivers, very efficient for heavy loads, so barges and ships are the most efficient competitors where this network exists.

The tendency for heavy haulage in recent years has been in reduction, mainly due to the closing of mines and the location of electricity power stations near harbours and rivers or canals.

In fact, in Germany and Poland, mines are still in operation, but in France for example, the last one closed in 2004.

So there is no obvious great market that can make an immediate decision of increasing axle loads.

At the same time the traffic of passengers is high in Europe, and the speeds are high:

9 billion passengers and 600 billion passenger-kms in 2002.

So it is difficult to assimilate one traffic with the other, especially long distance passengers and slow heavy freight.

Both local and long distance passenger traffics are concerned, and it is difficult to develop itineraries dedicated to freight, even if several examples can be shown, of dedicated or half-dedicated with local passenger traffic.

However we estimate that heavy haulage has a potential of 10 % to 30 % of the total railway freight traffic in Europe, and can be profitable.

A lot of European railways have made studies or experiences that seem to be positive.

The evolution that has been made in the 1980’s, when the maximum axle load was increased from 20 to 22.5 t on a lot of lines, probably won’t be the same between 22.5 and 25 t, because the needs are different, and because there are other ways to improve capacity and productivity: for example, experiments are made on long trains up to 1.5 km, which is not easy because of the signalling system and the lack of space to park such long trains.

But we can consider that this evolution will occur in a lot of countries, especially for important freight lines. For dedicated lines, the experience of Scandinavia with 30 tons per axle could be useful for other countries.

5 Conclusion

In conclusion, the techniques are available in Europe for heavy axle load. Scandinavia already has the experience of up to 30 tons per axle.

The new E category (25 t) will probably become the standard of specialized freight lines that will be developed in relation to the market and to the possibilities of the networks.

For specific purposes, 30 t or even more will probably be developed, as well as the one line that already exists in Sweden.

6 Bibliography

- ERRI Report D 161 RP3: Dynamic vehicle/track phenomena, from point of view of track maintenance, 1988
- ERRI Report D 161 RP4: Dynamic effect of 22,5 t axle loads on the track, 1987
- ERRI Report D 173 RPI: Rolling contact fatigue, 1990
- Feindrich, Lothar: UIC/ERRI experience in measuring and assessing track fatigue as a consequence of increasing axle loads, papers on HAL workshop, 1990
- Florom, Robert L.: FAST/HAL mechanical component test, papers on HAL workshop, 1990
- Hannafious, Jon: FAST/HAL turnout and frog performance experiment, papers on HAL workshop, 1990

• **Larsson, D. and J. Gunnarsson**: A model to predict track degradation costs, 7th International Heavy Haul Conference, 2001

• **Lunden, R., Th. Nordmark, B. Paulsson**: Enhancing iron ore transportation in Sweden, 7th International Heavy Haul Conference, 2001

• **Nordmark, Th.**: Heavy haul operations in Sweden and the formation of the Nordic Heavy Haul Group, 7th International Heavy Haul Conference, 2001

• **ORE/ERRI Report D 141 RP5**: Effects on the track of raising the axle load from 20t to 22.5t, 1982

• **Read, David M. and Duane E. Otter**: FAST/HAL track load evaluation, papers on HAL workshop, 1990

• **Reiff, Richard P.**: Introduction to the FAST/HAL program, papers on HAL workshop, 1990

• **Roney, Michael D. and David K. Meyier**: A case study of wheel/rail cost reduction on Canadian Pacific railway’s coal route, 7th International Heavy Haul Conference, 2001

• **Scheurer, Bob**, QR, Australia: Queensland welcomes IHHA and AusRail delegates.

• **Tournay, Haary**: Heavy haul in South Africa, 7th International Heavy Haul Conference, 2001

• **Trevizo, M. Carmen**: FAST/HAL ballast and subgrade experiment, papers on HAL workshop, 1990


• **Zaremski, A.M.**, The economics of Increasing axle loads, ZETA-TECH Associates, USA, European Railway Review, 1999